A NEAR-TERM CONCEPT FOR TRAJECTORY-BASED OPERATIONS WITH AIR/GROUND DATA LINK COMMUNICATION

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Abstract

An operating concept and required system components for trajectory-based operations with air/ground data link for today's en route and transition airspace is proposed. Controllers are fully responsible for separation as they are today, and no new aircraft equipage is required. Trajectory automation computes integrated solutions to problems like metering, weather avoidance, traffic conflicts and the desire to find and fly more time/fuel efficient flight trajectories. A common ground-based system supports all levels of aircraft equipage and performance including those equipped and not equipped for data link. User interface functions for the radar controller's display make trajectory-based clearance advisories easy to visualize, modify if necessary, and implement. Laboratory simulations (without human operators) were conducted to test integrated operation of selected system components with uncertainty modeling. Results are based on 102 hours of Fort Worth Center traffic recordings involving over 37,000 individual flights. The presence of uncertainty had a marginal effect (5%) on minimum-delay conflict resolution performance, and wind-favorable routes had no effect on detection and resolution metrics. Flight plan amendments and clearances were substantially reduced compared to today's operations. Top-of-descent prediction errors are the largest cause of failure indicating that better descent predictions are needed to reliably achieve fuel-efficient descent profiles in medium to heavy traffic. Improved conflict detections for climbing flights could enable substantially more continuous climbs to cruise altitude. Unlike today's Conflict Alert, tactical automation must alert when an altitude amendment is entered, but before the aircraft starts the maneuver. In every other failure case tactical automation prevented losses of separation. A real-time prototype trajectory trajectory-automation system is running now and could be made ready for operational testing at an en route Center in 1-2 years.

1 Introduction

In recent years air traffic management research has focused on greater use of flight trajectory predictions and air/ground data link communication as a basis for a better air traffic control system. High-level concepts for the use of trajectory-based automation as the basis for a next-generation air traffic control system are being developed in the United States and in the European Union [1, 2, 3]. More detailed concepts that employ trajectory-based automation, air/ground data link, and higher levels of automation for separation assurance to increase airspace capacity have been proposed and studied in laboratory analysis and human-in-the-loop simulations [4,5,6]. It is generally accepted that air/ground data link, especially when integrated with trajectory automation, has good potential to improve controller productivity and enable better services for airspace users [7,8,9,10]. Data link communication for control clearances and pilot requests is operational in oceanic airspace, and

in the Maastricht Upper Air Center since about 2002 [11].

The use of trajectory-based automation to implement time/fuel-efficient flight trajectories in today's airspace with today's data link and today's fleet mix has not been demonstrated. Simulations have shown promising results, but operational testing is now needed to identify specific requirements for a first implementation of Trajectory-Based Operations (TBO) in the US national airspace system. The overarching goal of this work is to build a prototype system that can be tested in today's environment with today's equipage. Given the expense of new ground automation and especially new aircraft equipment, it is incumbent on the stakeholders to thoroughly examine what benefits can be achieved with currently available capabilities. An operational test would uncover benefits that may be realized over the next several years, identify specific requirements for implementation of TBO in the FAA's En Route Automation Modernization (ERAM) system, and guide future research.

This paper proposes a TBO concept and its required automation system that can be tested in the near term (2012 time frame) using currently available air/ground data link communication capabilities and today's fleet mix in US en route and transition airspace (generally above 10,000 ft). The objectives of the paper are to:

- define the near-term operating concept and its critical automation components,
- conduct a laboratory simulation to test integrated operation of selected (but not all) components: minimum-delay conflict resolutions, wind-favorable routes, better conflict detections, uninterrupted climbs and fuel-efficient descents (without metering), and independent tactical detection and resolution as a safety net,
- focus on trajectory and conflict analysis with uncertainty modeling (but without human operators in the loop),
- base the analysis on 100 hours of en route Center traffic data from today's US national airspace system, and
- prepare the prototype system for human-in-the-loop testing with controllers and pilots.

More recent concepts [4,6] targeted for year 2025 operations are blended with prior work on controller Decision Support Tools [14,15,24,51] into a concept for today's air traffic environment. Controllers are fully responsible for separation as they are today; currently available and fully operational capabilities for integrated operation of the Flight Management System with air/ground data link and Controller Pilot Data Link Communication (CPDLC) [7] are assumed for equipped aircraft.

The remainder of the paper includes the following sections: Section 2 describes the operating concept and its required trajectory automation components and their interoperability; Section 3 describes the laboratory simulation methodology and the uncertainty modeling approach; Section 4 describes the results including the test conditions, overall performance metrics, and examines failure cases (losses of separation) and how their circumstances and causes suggest requirements needed to make the concept workable in real-world operations; Section 5 states the conclusions.

2 Operating Concept

Trajectory-Based Operations are those airspace operations in which the future trajectories of all aircraft, i.e., their four-dimensional (4D) paths through space and time, are the basis for separation and efficient flow in the airspace. 4D trajectories are predicted and regularly updated by an automation system and used to solve traffic conflicts, satisfy metering constraints, avoid weather and restricted airspace, and find more efficient flight paths all in an integrated manner. It is important to understand that the calculation of a 4D trajectory and the integrated detection and resolution of airspace problems does not imply that aircraft are necessarily required to track their predicted trajectories, for instance through the assignment of a required time of arrival (RTA) at each waypoint. The goal is to make trajectory predictions accurate enough, and updated frequently enough, so that conflict detections are robust and time constraints are issued as part of a trajectory clearance only

when necessary. This reduces constraints and makes the concept suitable for all aircraft regardless of their equipage and performance level. Aircraft able to meet time constraints will do so when necessary and therefore be able to fly in flows that may require precise tracking to achieve a desired result like a minimum-fuel descent in medium to heavy traffic or precise time-based metering for other reasons. Lesser equipped aircraft are still handled using trajectory automation and most of the time fly without the need for time constraints, but under certain conditions and in certain regions may have to fly a less optimal profile because they are unable to accept an RTA constraint.

Shown in Figure 1 is a top-level diagram of the architecture upon which the operating concept is based. The concept is derived from the Advanced Airspace Concept [4], but with some important differences that make it more suitable for today's operations. For example, in this concept controllers are fully responsible for separation, and controllers determine whether or not to issue all trajectory changes. During most operations the controller interacts with the Controller Interface (Section 2.2), the Strategic Automation component (Section 2.1), and the Air/Ground Data Link Communication (Data Comm) component (Section 2.3) to maintain separation, minimize delay, manage pilot requests, find better trajectories, and generally manage traffic flow.

Strategic Automation advises trajectory-based clearances that are time- and/or fuel-efficient, conflict-free (see *Assumptions* later in this section), metering compliant and avoid weather. Integrated FMS/data link is used for control clearances and pilot requests for equipped aircraft, and for downlink of selected aircraft parameters for improved trajectory modeling [50] and conflict detection. An independent Tactical Automation component (Section 2.4) provides a safety back-up to help protect against loss of separation and operates much like today's Conflict Alert, except with better missed/false alert performance [12]. The Traffic Alert and Collision Avoidance System (TCAS) works as it does today to prevent collisions.

Three tiers of automation ensure safe separation and prevent collisions. Strategic Automation works on a 20-min time horizon and solves most problems with efficient continuous trajectory clearances; Tactical Automation works on a 3-min horizon to help maintain legal separation with minimal consideration for trajectory efficiency; and TCAS works on about a 1-min horizon to prevent collisions.

One common system for all levels of aircraft equipage and performance ensures consistency and coordination in mixed equipage operations. It also simplifies operations for the controllers and the service provider since they work with and maintain one common system. Trajectory-based clearances are tailored to aircraft equipage.

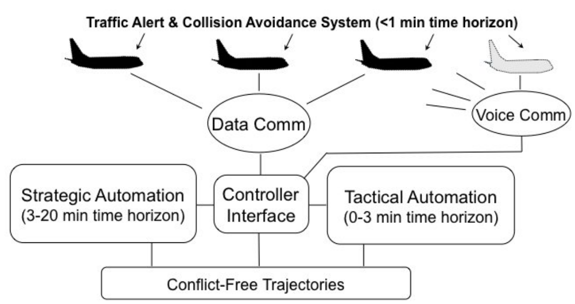


Figure 1. Trajectory automation system top level diagram

The remainder of this section describes in more detail the sub-functions within Strategic Automation, the Controller Interface, Data Comm, and Tactical Automation.

But first, we list some important assumptions upon which the concept and its automation components are based. These assumptions are based on about 15 years of research in trajectory automation and human/automation concepts for conflict detection and resolution, time-based metering, data link, and separation assurance automation for en route and transition airspace.

Assumptions

- En route center air traffic controllers are consistently favorable towards conflict-free,

adjustable, advisory solutions to air traffic control problems [13,14,15,16].
- Interactive, graphical user interface functions with a rapid-feedback (0.1 sec response, see Section 2.2) two-way connection to trajectory and conflict analysis automation are well-suited to the Center radar controller's primary (R-Side) traffic situation display [14,15,16].
- Currently available integrated FMS/data-link can increase controller productivity and thereby enable more efficient operations, and can support many of the route and altitude clearances envisioned for Trajectory-Based Operations [11,17,18].
- There is plenty of usable airspace to improve trajectory efficiency and save fuel if uncertainties can be reduced or accommodated [14,19,20].
- A trajectory-based automation system is acceptable and beneficial if the majority (but not all) of its advised solutions are conflict-free for a specified time horizon (e.g., 10-15 min). Since trajectory and conflict detections update rapidly (every 12 sec), it is not necessary that all advisories are guaranteed to be conflict-free. The limits of this assumption are a function of time horizon, traffic conditions, and automation sub-element (e.g., metering or wind routes).

2.1 Strategic Automation

The Strategic Automation function employs real-time rapid-update (every 12 sec) 4D trajectory modeling and conflict analysis to identify minimum-delay, fuel-saving flight trajectories that are conflict-free, compliant with time-based metering constraints, and avoid convective weather to the extent possible. Specifically it computes trajectories and provides associated clearance advisories for:

- Fuel-efficient descents from cruise altitude to the meter fix,
- Minimum-delay weather avoidance trajectories,
- Wind-favorable routes,
- Multi-trajectory conflict detection for climbing flights, and
- Minimum-delay conflict resolution trajectories.

Clearance advisories are in the form of route, altitude, and speed changes commonly used in today's air traffic operations and compatible with air/ground datalink communication. The controller may issue clearances as advised, modify the proposed trajectory (and its associated clearance) using automated user interface functions, or reject the advisory altogether and generate their own solution, perhaps for reasons not considered by the trajectory automation system. The following general characteristics of the Strategic Automation function are central to its operation and its interoperability with controllers and pilots:

- Trajectory solutions are integrated in the sense that all trajectory solutions account for separation, metering, weather, and airspace user preference to the extent possible.
- A common trajectory automation system serves all levels of aircraft equipage and performance and all proposed trajectory changes, whether they be automatically generated and presented as an advisory or manually generated by the controller using interactive functions to solve a problem (e.g., separation, metering, or weather conflict) or evaluate a pilot request.
- Trajectory changes are closed and continuous in that a single clearance results in a new trajectory that solves a problem or implements a more fuel- or time-efficient path and returns the aircraft to its nominal route or altitude profile [4,18]. This reduces the number of required clearances, allows controllers and pilots to see and evaluate the full clearance, and helps keep aircraft in conformance with their flight plan.
- The system automatically and continuously identifies and advises opportunities for more time- and/or fuel-efficient flight trajectories, and the controller interface makes them easy to evaluate, modify if necessary, and issue as clearances.

2.1.1 Fuel-Efficient Descents

The concept combines the trajectory automation and controller interface functions of the Efficient Descent Advisor (EDA) [15,21] and the Arrival Manager [22]. The objective of both functions is to compute speed, path stretch, and altitude clearances that enable fuel-efficient, conflict-free descents to the arrival meter fix in all traffic conditions, particularly in medium to heavy traffic where time-based metering is balancing arrival demand with airport capacity. Solutions are weighted toward speed and path stretch to keep the aircraft high and save fuel; altitude is used when needed, for example if a path stretch is too long. Research shows that substantial fuel savings could be realized if these functions could enable aircraft to fly continuous near-idle thrust descents in medium to heavy traffic [23,47]. Both functions attempt to adhere to the sequence and schedule constraints generated by the Traffic Management Advisor, a time-based metering tool that efficiently balances arrival demand with airport capacity and is now deployed at all 20 US en route Centers [24]. EDA generates trajectory advisories in response to metering conflicts where estimated meter fix arrival time deviates from TMA scheduled arrival time. The Arrival Manager generates trajectory advisories in response to both metering and traffic conflicts to maintain conflict-free arrival flows that are metering compliant to the extent possible.

2.1.2 Weather Avoidance

The Weather Avoidance function serves two purposes. It helps ensure that trajectory-based solutions to other problems (wind routes, path stretch for metering, conflict resolutions) don't maneuver aircraft into convective weather. Also, it provides a basis for computing minimum-delay reroutes around weather. Weather modeling is based on the Corridor Integrated Weather System (CIWS) and the Convective Weather Avoidance Model (CWAM) [25,26]. Weather detection is on about a 30 min time horizon, and weather models are assumed to be deterministic. It is anticipated that the following hierarchy of weather avoidance capabilities of increasing complexity will form the basis for weather avoidance in trajectory-based operations:

- A graphic display of weather is shown on the traffic display.
- Whenever the Trial Planner (see Section 2.2) is activated, the controller is alerted if the trial plan trajectory penetrates a modeled weather cell. The weather probe accounts for cloud tops and includes a suitable separation buffer for alerting.
- Weather avoidance is integrated with the automatic trajectory advisory functions and trajectory solutions are not advised if they are expected to penetrate a weather cell.
- The trajectory automation automatically computes a minimum-delay reroute that avoids weather and is conflict free [22,27].

2.1.3 Wind-Favorable Routes

Sometimes aircraft in flight can reduce flying time and save fuel by flying routes that are more wind-favorable than their current route of flight [28]. Operational testing in 2001 showed potential to save 900 flying minutes per day in Fort Worth Center airspace using trajectory automation that automatically performs a wind-route analysis on all flights to identify those that can save at least 1 min by flying direct to a downstream fix on their route of flight [14]. Laboratory analysis of the Direct-To concept using nationwide traffic data showed potential for \$200M per year savings in fuel costs (assuming \$29/min operating costs), and no appreciable effect on the spacial distribution of traffic conflicts [29]. Wind-optimal routes where routing is optimized could save even more [30,31].

The Strategic Automation function automatically identifies wind-favorable routes that are compliant with downstream metering constraints, avoid convective weather, and are conflict-free for specified amount of time, e.g., 10-15 min. The system may be configured to advise wind-favorable routes to controllers or to compute them upon request by a controller, perhaps in response to a pilot request. The controller may easily adjust the downstream capture fix for operational considerations or other factors. Regardless of the capture fix

selection, the Trial Planner always shows the difference in flying time between the current trajectory and the trial plan trajectory.

2.1.4 Multi-Trajectory Conflict Detection for Climbing Flights

In today's operations, errors in climb and descent predictions or incomplete knowledge of intent (e.g., speed profile) result in conservative and sometimes inefficient procedures that keep climbing and descending traffic flows well separated to ensure safety. Climb and descent trajectory prediction errors are caused by a number of factors, including errors in aircraft weight, aircraft performance models, thrust setting, wind, and speed intent. Errors in aircraft weight alone can cause substantial errors in trajectory-based climb predictions resulting in late (approximately 2 min to loss of separation) conflict detections involving climbing flights [32,33]. For example, a 10% error in weight for an MD82 aircraft causes a 3-mile (25 sec) error in predicted top of descent; a 10% increase in weight (relative to nominal) for a climbing MD82 causes the aircraft to reach its top of climb 16 nmi later.

Controllers often issue temporary altitude clearances to level off climbing aircraft to resolve conflicts with crossing or in-trail traffic at higher altitudes. In some cases temporary altitude clearances are part of the hand-off procedure from the low to high altitude airspace sectors. The low sector controller clears the aircraft to the highest altitude in the low sector. Then the high altitude controller takes the hand-off and clears the aircraft to higher altitudes after confirming the climb is conflict-free. Climb uncertainty and the associated use of temporary altitudes can cause unnecessary clearances adding to frequency congestion and in some cases unnecessary level segments. Better conflict detection for climbing flights could improve these procedures and enable more uninterrupted climbs to cruise altitude.

Improved strategic conflict detection logic for climbing flights based on the use of high-rate and low-rate climb trajectories has been proposed and tested [34]. High-rate and low-rate climb trajectories define a dynamic vertical and horizontal detection criteria around the nominal trajectory of the climbing flight at each trajectory time step. The legal vertical separation criteria (usually 1000 ft) is added to the dynamic conflict detection limits.

2.1.5 Minimum-Delay Conflict Resolutions

The Trajectory Automation system attempts to calculate as many as five types of resolution trajectories (path stretch, direct-to, offset, altitude, speed) for each aircraft in a detected conflict pair. Resolution trajectories are ordered by delay, where delay is the difference in flying time between the nominal trajectory and the resolution trajectory for the maneuvered aircraft. In some instances delay can be negative, i.e., a flying time savings, for example when a resolution includes a direct route to a downstream fix. Other metrics such as fuel savings could be computed for each resolution trajectory.

The automatic conflict resolution algorithm (autoresolver) developed at NASA Ames as part of the AAC is used in this analysis [22,35]. The autoresolver handles the complete spectrum of conflict types found in en route airspace, and resolution trajectories are patterned after changes to flight plans, altitudes, and speed profiles that controllers customarily issue to pilots in today's operations.

Conflict resolution trajectories are automatically computed and available for review by the controller when conflict detection parameters satisfy a pre-set criteria (defined in Table 1 for this study). The system advises the resolution trajectory with the minimum amount of delay regardless of which aircraft maneuvers. Alternatively the controller may request a minimum-delay maneuver for a selected aircraft, or request a certain type of maneuver for a selected aircraft, e.g., a route change that starts with a left turn, perhaps for reasons not considered by the automation system.

2.2 Controller Interface

The controller interface functions are fully integrated with the radar controller's primary (R-Side) traffic situation display. Clearance advisory information is displayed in list format and/or in the flight data block. An interactive rapid-feedback Trial Planner function [14,36]

enables the controller to quickly display and evaluate a trajectory advisory and its corresponding clearance, modify the advised trajectory if necessary, create their own trajectory change, evaluate a request from a pilot or an Airline Operations Center (AOC), or implement a trajectory change generated by the Traffic Management Unit (TMU). The following characteristics of the Controller Interface are considered critical to achieving the objectives of this concept:

- A high-speed two-way connection between the Controller User Interface and the Strategic Automation function that enables rapid-update (0.1 sec response time) of the trajectory graphics and information about the trial trajectory relative to other traffic (conflict and metering status) and convective weather in response to controller inputs. Status information includes flying time and/or fuel burn metrics of the trial plan trajectory relative to the current trajectory.
- A flight plan amendment consistent with any trajectory change is automatically formatted and dynamically updated and always ready for input to the Center Host computer (or ERAM) and uplink to datalink equipped aircraft via a single keyboard or track ball entry.
- The presence of automatically generated trajectory-based clearance advisories is indicated in the flight data block using minimal additional text (1-4 characters) and/or in an optional list format. A point and click action on the advisory automatically initializes the Trial Planner with the advised trajectory clearance, the associated Host (or ERAM) flight plan update, and a datalink message for equipped aircraft. The controller may then issue or modify the clearance as described above.

This automated rapid-feedback Trial Planner-based user interface concept has been evaluated in numerous and varied simulations over the years [21,36,37] and during operational field testing at en route Centers [13,14]. It is well suited to the R-Side traffic situation display and, especially when integrated with data link, is expected to substantially increase controller productivity enabling controllers to spend more time on efficiency related services for airspace users.

2.3 Air/Ground Data Link Communication

Air/ground data link communication is expected to be a key enabler for more efficient, higher capacity air traffic operations. Controllers can provide better service because their voice communication workload is reduced, particularly in the exchange of routine clearances like transfer of communications. Equipped aircraft can easily accept and fly more complex trajectories based on latitude/longitude waypoints for fuel-efficient descents, minimum-delay weather avoidance, and wind-optimal routes. Data entry errors are reduced since complex information does not have to be entered by hand into an aircraft Flight Management System (FMS) that is integrated with datalink, and amendments are automatically sent to the Host (or ERAM).

Research suggests that existing FMS integrated with air/ground data link communication capabilities and Controller Pilot Data Link Communication (CPDLC) can support many of the route and altitude clearances envisioned for this concept [18, 38]. Operational flight trials of CPDLC in the Miami Center between 2002 and 2004 demonstrated a capability to exchange routine messages between air and ground (e.g. transfer of communications and altimeter settings) that provided significant controller workload savings [7]. However, those trials did not investigate the more complex route and altitude messages proposed here. CPDLC was successfully evaluated operationally by Eurocontrol starting with the PETAL-II project in 1998 [8,9] and continuing as Link2000+ in the Maastricht Upper Air Center (UAC) airspace today [11]. This system allows pilots to request altitudes and direct routes to downstream fixes, while controllers can send altitude, route and other basic profile-changing messages along with the routine messages used in the Miami Center trials [11,7].

The principal difference between the Link2000+ program and that proposed here is the additional use of more complex, closed-loop trajectory changes for time-critical applications that do not require cumbersome voice read-back, and the addition of ground-based automation to simplify the creation and transmission of these more-efficient clearances. These trajectory changes require only a few messages to implement most lateral (um74 and um79) and vertical (um20 and um23) flight plan amendments [18,39]. Procedures for the implementation of these clearances on the flight deck were explored in several studies [17,18]; those studies concluded that only small modifications to generic flight deck procedures used on oceanic, datalink-equipped aircraft today were necessary to implement flight plan amendments received via datalink. The additional use of an "integrated FMS/datalink" capability simplifies flight deck procedures by enabling crews to load and view a route or altitude clearance on the aircraft's navigation display, automatically execute the clearance through the auto-pilot, and send a wilco response (or "unable") to the ground system.

The Future Air Navigation System (FANS)-1/A equipment package includes CPDLC integrated with the aircraft's FMS, Automatic Dependent Surveillance – Contract (ADS-C) for the exchange of aircraft state data, and improved surveillance systems (i.e. GPS-based), and it could be made available on the large majority of aircraft flying today. FANS-1/A is currently operational on most aircraft that fly oceanic routes, and virtually every new commercial aircraft entering service today is equipped with at least a latent FANS capability. As of 2007, the most recent data available [40], the Boeing fleet in service with the ten largest carriers included 9.6% that actively employed FANS. Another 25.4% of that fleet has FANS capability onboard but not operational, principally because the aircraft does not fly through airspace in which FANS services are currently offered. The largest percentage of the fleet, 52.2%, could be retrofitted to include FANS, and in many cases that is already happening because the old FMSs are being replaced with more-capable FMSs to overcome navigation database capacity limitations. The remaining 12.8% of the fleet, which is being retired fairly quickly because those aircraft are relatively fuel-inefficient, do not have a clear upgrade path to FANS. In addition to upgrading or equipping non-FANS aircraft with the hardware required to support this TBO concept, air carriers will have to invest in crew training and procedure development, and may potentially bear costs when aircraft are taken out of service for hardware installation. However, with 87.2% of the fleet in 2007 either FANS-equipped or with a clear path to equipping the fundamental limiting factor for an initial implementation of TBO is not likely to be aircraft equipage.

Weather avoidance and wind-optimal routes are especially well suited for datalink-equipped aircraft. For example, a minimum delay weather reroute is unlikely to be a simple vector or to pass through a single named waypoint before rejoining the original route, the only kind of trajectory changes that can be routinely passed to voice-equipped aircraft. Rather, the reroute will generally consist of one or more lat/long-defined waypoints that can be uplinked to FANS aircraft and automatically loaded into and flown by the FMS.

2.4 Tactical Automation

The Tactical Automaton component is based on a tactical conflict detection and resolution function called TSAFE (Tactical Separation-Assured Flight Environment) [12]. TSAFE is intended to provide an independent back-up to Strategic Automation to detect, and optionally help resolve, any conflicts left unresolved with less than approximately 2 min to predicted loss of separation [41,48]. TSAFE uses both dead-reckoning (constant velocity) and flight plan-based trajectory predictions to account for uncertain pilot intent. It has been tested using recorded Center radar tracking data for many actual operational error cases (losses of separation due to controller error) and with recordings of busy Washington Center traffic. The results show that TSAFE generally provides earlier and more reliable alerts and fewer false alerts than Conflict Alert, the legacy

tactical conflict alerting component for controllers. A key feature of TSAFE is that it probes a proposed altitude change for conflicts immediately after a controller enters the altitude amendment, without having to wait for the flight to actually start climbing or descending. This feature can prevent many losses of separation that are caused by bad altitude clearances mistakenly issued by controllers in today's operations.

TSAFE provides alerts starting at 3 min to loss of separation with a user interface that is expected to be much like that of today's Conflict Alert. If the controller determines that a tactical maneuver is required, the controller issues the maneuver clearance using radio communication as they do today.

It is important to note that TSAFE resolution maneuvers, like vectors or altitude clearances issued today, are not required to be part of closed continuous trajectories. The primary objective of a TSAFE maneuver is to get the aircraft on a safe vector or altitude that is conflict free for 3 min, with minimal consideration of overall trajectory efficiency. This simplifies the TSAFE logic, and with a few exceptions (that need more research), keeps TSAFE independent of Strategic Automation.

Consider the scenario where uncertainty in pilot response time (or surveillance data) triggers a TSAFE alert because TSAFE has not yet sensed that the aircraft is responding to a previously issued Strategic Automation clearance. Perhaps the pilot starts maneuvering later than expected, and/or the strategic maneuver is in response to a relatively late strategic (e.g., 4 min) conflict detection. Under these conditions the controller, or a tactical resolution system, might first consider a tactical clearance that is consistent with the previously issued strategic clearance. Alternatively, the controller issues whatever they deem necessary to maintain safe separation.

Following a tactical maneuver, Strategic Automation attempts to build a closed continuous trajectory that returns the maneuvered aircraft to its nominal route of flight or altitude profile.

3 Simulation Analysis

The objective of the simulation analysis is to test elements of the trajectory-based automation system under a variety of traffic conditions using 100 hours of actual en route Center traffic recordings (radar track and flight plan data) but without humans in the loop. 100 hours was arbitrarily chosen as suitable to reflect a wide variety of traffic conditions. Laboratory simulations without human operators enable testing with more traffic data than is practical for simulations with controllers and pilots. Uncertainty modeling is incorporated into the trajectory predictions and pilot response models to make the results more representative of real-world operations. A secondary objective was to use the same real-time software baseline that will be used in subsequent human-in-the-loop simulations to help prepare the system for simulations with controllers and pilots.

3.1 Simulation Approach

The simulation approach flies all aircraft on trajectories that are consistent with the route and altitude flight plan intent that is in effect when they fly into the airspace. Trajectory changes are made only in response to detected conflicts and/or opportunities for more efficient flight trajectories. This approach [6,33] is implemented using the Center/TRACON Automation System (CTAS) trajectory analysis methodology and software [42,43,44]. Recorded en route Center traffic data, NOAA RUC-2 weather data, and a database of aircraft performance models are the primary inputs to CTAS. The simulation "takes control" of aircraft as they enter Center airspace and flies them based on the flight plan intent (route and altitude), position, and speed that was in effect at the track point where they were initialized. This enables the use of actual traffic to initialize the simulation, but removes the actions of the real air traffic controllers and allows the trajectory automation to be the only driver of trajectory changes. This approach makes it easy to convert any Center traffic recording into a simulation scenario, and facilitates direct comparison of simulated and actual traffic flows.

For each simulation run, every aircraft in a full Center traffic recording is initialized at the first radar target that is at or above 11,000 ft *and* is preceded by at least 4 prior radar track updates. Waiting for the 5th track update gives the CTAS ground speed filters time to stabilize and thereby provides a more accurate speed to propagate aircraft through the simulation. Requiring aircraft to be at 11,000 ft ensures that most aircraft have started their climb following departure from Terminal Radar Approach Control (TRACON) airspace. On initialization, temporary altitudes are removed for any climbing aircraft with an active temporary altitude in its Host flight plan.

Whenever a new aircraft is initialized into the simulation, a "radar track" trajectory is computed and becomes the basis for all subsequent simulated 12-sec radar track updates. When the trajectory automation inputs a flight plan amendment for any other reason (e.g., conflict resolution, wind route) a new radar track trajectory is computed based on the new flight plan or speed intent information.

3.2 Uncertainty Modeling

The operation and performance of any air traffic control system is strongly influenced by the level of uncertainty in the system. The results of any proposed concept for air traffic control must be viewed in the light of the uncertainty environment under which it was tested.

Trajectory prediction uncertainty errors are modeled and added to the radar track trajectories for all aircraft in the simulation. Adding uncertainty to the radar track trajectories ensures that all trajectory predictions in the simulation are influenced by uncertainty to the extent that uncertainty factors are modeled. It also ensures that both conflict detections and trajectory changes (conflict resolutions, wind routes, etc) are influenced by uncertainty as they are in the real world.

An analysis was performed to quantify the level of uncertainty in these simulations, and compare simulated uncertainty to real-world prediction uncertainty using the common CTAS trajectory automation system software. Appendix A includes trajectory prediction error histograms based on CTAS predicted trajectories vs. actual Host traffic, and CTAS predicted trajectories vs. the simulated radar track trajectories with the uncertainty modeling used in this analysis.

3.2.1 Maneuver Execution Delay

The period of time between the issuing of a trajectory clearance by a controller and the actual execution of that clearance by the aircraft is referred to as the maneuver execution delay; this delay must be both accommodated by the concept and modeled in a realistic way in the simulation. The data used to model distributions of execution delay times were gathered in two pilot-in-the-loop simulations of TBO using a high-fidelity, Level D-certified 747-400 simulator [18], twenty two pilots, and the exchange of more than 200 horizontal and vertical flight plan amendments. Significantly different response times were found for these two types of flight plan amendments so two different response time models were created using Gamma distributions. Its cumulative distribution function, ***p=F(x|a,b)***, is calculated according to

$$p = F(x \mid a,b) = \frac{1}{b^a \Gamma(a)} \int_0^x t^{a-1} e^{\frac{t}{b}} dt$$

$$\Gamma(a) = \int_0^\infty t^{a-1} e^{-t} dt$$

where the parameters ***a*** and ***b*** describe the shape of the distribution. The best fit parameters for the horizontal-plane trajectory changes are ***(a,b) = (6.08,9.89)***; for the vertical trajectory changes the values are ***(a,b) = (9.64, 3.81)***. The median execution delays are 56 sec for route amendments and 39 sec for altitude amendments. These delay models are consistent with delay times reported for similar flight plan amendments during the Preliminary Eurocontrol Test of Air/Ground Data Link Phase 2 trials with in-service aircraft [8,9]. The delay time for a particular maneuver is selected according to a lookup table containing the delay times of each distribution function.

The median response time delay is used to predict the trajectory the aircraft will fly when the flight plan amendment is sent. The automation-calculated trajectory that includes this delay is shown to the controller, but the flight plan amendment uplinked to the aircraft does not include that deterministic (median) delay time – if it did then 50% of aircraft would fly past the maneuver execution delay point before they had accepted the new flight plan. In some situations an explicit maneuver execution point is placed along the route of flight approximately 120 sec ahead of the aircraft, for example when excessively early or late execution of the amendment would create a conflict with another aircraft or when an aircraft is required to meet a metering time at a fix; however, this constraint reduces the number of trajectory-change options available to the controller and is used only when necessary. In the current simulation this latter functionality is never exercised.

In this simulation analysis all trial plan trajectories include a maneuver execution delay segment that starts at the current track position and extends a constant maneuver execution delay time out along the dead reckoning trajectory. The dead reckoning trajectory is the projected path of the aircraft based only on a filtered ground speed velocity vector computed using the last 5 radar track updates. Actual maneuver execution start times used to generate the radar track trajectories are selected randomly according to the Gamma distribution for each new maneuver in the simulation.

3.2.2 Aircraft Weight

Aircraft weight errors in this analysis were modeled based on the actual variation in observed takeoff weight among 11 common aircraft types [45]. Weight variation was modeled as a truncated Gaussian distribution with lower and upper limits based on these actual observed weights. The mean of this distribution was set to the nominal CTAS value of 90% of the maximum gross takeoff weight. This is because the altitude trajectory prediction errors have zero mean when using this value [32]. The standard deviation was set to 10% of the maximum gross takeoff weight in the CTAS database based on the median of the standard deviations of observed weight variation among the 11 aircraft types of 7.7%. The lower and upper limits of the truncated Gaussian distribution were set at 80% and 100% of max gross take-off weight respectively, in order to maintain the truncated Gaussian distribution of the weight parameters in the simulation.

For each new aircraft in the simulation a weight for that aircraft is selected using the truncated Gaussian distribution. This weight is used to compute the initial radar track trajectory and any subsequent radar track trajectories for example in response to a flight plan amendment. The nominal aircraft weight (90% of max gross take-off weight) is always used by the automation system for trajectory predictions.

3.2.3 Wind Error

The Strategic Automation function (and CTAS) uses the National Oceanic and Atmospheric Administration (NOAA) Rapid Update Cycle 2-hour forecast model (RUC-2) [49]. The RUC-2 model is updated every hour. One objective in this analysis was to include a simple model of wind error. Schwartz, et al [46] conducted an error analysis of RUC forecast wind predictions, and their results show estimated wind error as a function of wind speed and other factors. [46, Table 4] shows that RUC-2 wind magnitude error ranges from 15-25% of average wind speed for speeds from 30 kt to greater than 50 kt. Their results also show that wind error generally increases with wind magnitude. In this analysis, a constant 20% error in wind magnitude is implemented. For all aircraft in the simulation, the radar track trajectories are computed using a wind magnitude that is 20% greater than the magnitude of each of the 40 km grid points in the RUC-2 forecast. No attempt was made to model other components of wind error.

4 Results

A subset of the trajectory automation functions in the concept were analyzed in laboratory simulations. The test conditions are summarized below. In all cases, fuel-efficient (near-idle thrust) descents to the meter fix are

modeled as the nominal descent trajectory. The automatic removal of temporary altitudes for climbing aircraft (described earlier) results in uninterrupted climbs to cruise altitude as the nominal climb trajectory. It should be clarified here that though fuel-efficient descents are modeled as the nominal descent trajectory, the application of the metering functions [21,22] is beyond the scope of this analysis. Conflicts between arrivals to a common meter fix are resolved without regard for time-based metering constraints. Integration of the EDA and the Arrival Manager with this system will be the subject of future work.

The simulation analysis is based on 102 hours of actual Fort Worth Center traffic recordings from 32 separate 3-hour and 4-hour samples from busy week-day periods on 30 different days in February, March, April and May of 2010. In total, the analysis is based on 37,631 individual flights.

Test Conditions

All simulation runs include Minimum-Delay Conflict Resolutions and process all traffic above 11,000 ft. Individual runs also include:

1. nominal climb conflict detection, real-time simulations, 102 hours of traffic.
2. Wind-Favorable Direct Routes, nominal climb conflict detections, real-time simulations, 32 hours of traffic.
3. Multi-Trajectory Conflict Detection for Climbing Flights (in place of nominal), real-time simulations, 23 hours of traffic.
4. Tactical Conflict Detection and Resolution, post-run replay of loss of separation cases from Test Conditions 1 and 2.

4.1 Minimum-Delay Conflict Resolution

The simulation runs were first configured to just resolve detected conflicts using the AAC autoresolver algorithm [35,22]. The autoresolver is implemented in Java and called from CTAS. Every 12 sec CTAS sends to the autoresolver all detected conflicts that meet the *detection criteria* in Table 1. The autoresolver returns multiple resolution options for each aircraft. CTAS computes trial resolution trajectories using the resolution parameters (route or altitude amendment or speed change) returned from the autoresolver. CTAS checks trial trajectories for conflict according to the *resolution criteria* in Table 1. The trial resolution trajectory analysis computes the time delay associated with each resolution (difference in time to fly resolution trajectory vs. current trajectory). The resolution that is conflict-free and has the minimum delay is implemented. If no conflict-free resolutions are found, the process repeats on the next conflict detection update until a conflict-free resolution is found. In CTAS, all trajectory predictions and conflict detections update every 12 sec. Once a successful resolution is found and implemented, a new radar track trajectory for the maneuvered aircraft is computed, and the flight plan or assigned speed is updated in CTAS and the conflict falls off the internal list of detected conflicts, usually on the next trajectory update.

Table 1. Strategic conflict detection and resolution criteria

	Detection	Resolution
Time to LoS (minimum/maximum)	2 min 8 min	0 min 15 min
Time to LoS, merging arrivals (minimum/maximum)	2 min 20 min	0 min 20 min
Horizontal separation	6 nmi	8 nmi
Vertical separation, both level	1000 ft	1000 ft
Vertical separation, one or both climbing or descending	1500 ft	2000 ft

In addition to the criteria in Table 1, adjustable parameters are used to configure the autoresolver. For example, in this analysis the maximum allowable turn angle for auxiliary waypoint maneuver is 60 deg, and the maximum range to a downstream return waypoint following an auxiliary waypoint maneuver is 350 nmi. In an auxiliary waypoint maneuver the aircraft flies direct to an off-route latitude/longitude point then returns to its nominal route at a downstream flight plan fix.

Shown in Figure 2 are the combined counts of conflict detections and conflict resolutions for the 32 simulation runs with and without uncertainty. The figure distinguishes between conflicts involving two arrivals merging to a common meter fix and all other conflicts. Resolutions were computed for 94% and 89% of conflicts for the no-uncertainty and uncertainty conditions respectively. The increase in overall conflict count for the uncertainty runs is due to conflicts recurring after an initial resolution was issued, and cases where the trial plan resolution did not detect a secondary conflict due to trajectory uncertainty. Most of the unresolved conflicts are a result of either short-time-horizon detections (2-3 min to LoS), short duration detections where the conflict is only valid for 2-3 trajectory updates (24-36 sec) and then goes away, or merging arrivals where a resolution was not found. It is expected that improvements to the resolution logic or suitable adjustments to run-time parameters will increase performance to near 100%. The merging arrival cases were replayed using a smaller detection and resolution criteria (5 nmi and 7 nmi respectively) and many of the unresolved arrivals pairs were resolved. In all cases, except for one specific category described later (Section 4.2), tactical automation detected the conflict and prevented a loss of separation.

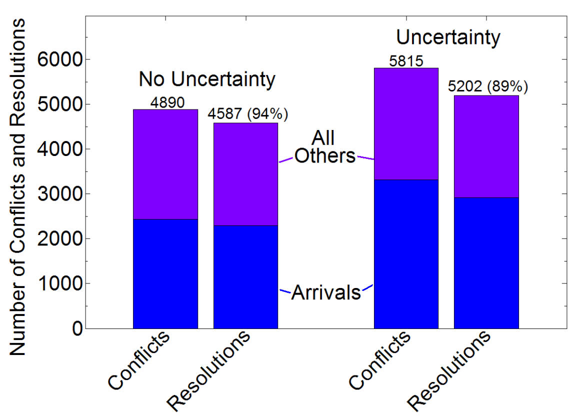
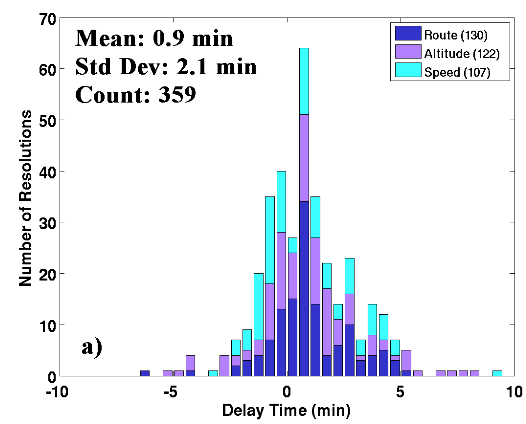


Figure 2. Strategic conflict detections and conflict resolutions.

Shown in Figure 3 are resolution delay histograms for simulation runs without uncertainty (Fig 3a) and with uncertainty (Fig 3b) from the traffic sample with the maximum peak traffic count (5/13/2010, 2100z start, 4 hour duration). The traffic sample includes 1553 individual flights above 10,000 ft, and the peak traffic level above 10,000 ft is 266 aircraft. The resolution delay results from a single run are shown here (Fig 3); the delay characteristics are similar for the other runs.

Note that many resolutions save flying time due to direct route segments or speed or wind differences. The time delay metric is most meaningful for the route changes and resolutions for merging arrivals. Other metrics such as fuel burn may be more important when considering speed and altitude change, but are not considered here.



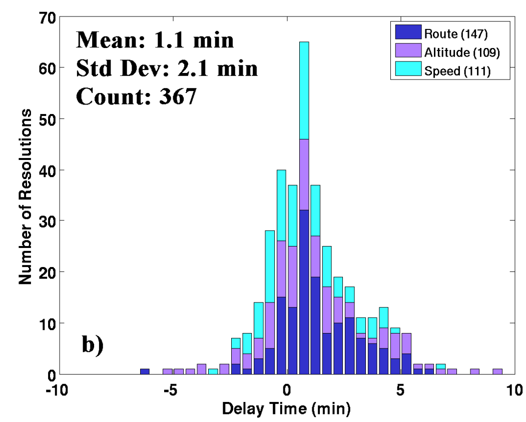


Figure 3. Resolution delay, peak traffic sample (05/13/10.21z): a) without uncertainty, b) with uncertainty.

The altitude amendments (Fig 3) with greater than 5 min of delay are due to cases where a temporary altitude was issued, but the time delay computation did not account for the return to nominal flight plan altitude. This can

cause large delay computations due to variations in wind and Mach number between altitudes. In the future, time delay calculations will model the expected return to flight plan altitude.

The important result depicted in Fig 3 is that delay due to resolution maneuvers is not significantly influenced by uncertainty to the extent it was modeled in the simulation. However, more conflicts (+19%) within the resolution time horizons (8 min and 20 min for arrival/arrival pairs) are detected and would nominally require a clearance (Fig 2).

For the run depicted in Fig 3, 267 out of 1553 aircraft in the simulation (17%) received one or more conflict resolution clearances (about 3% received 2 clearances; 1% received 3 clearances; 5 aircraft received 4 clearances).

Figure 4 shows resolution delays separately for conflicts between two arrivals (to Dallas/Fort Worth International or Dallas Love Field) merging to the same meter fix, and all other conflict pairs. Note that there are very few altitude amendments for merging arrivals, reflecting the desire to keep merging arrivals on their fuel-efficient profile to the extent possible.

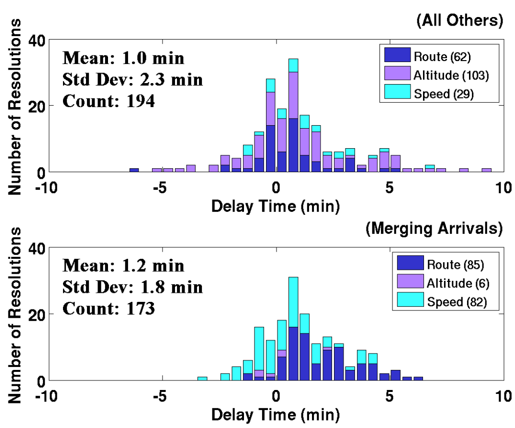


Figure 4. Resolution delay, peak traffic sample (05/13/10.21z), with uncertainty: a) all except merging arrivals, b) merging arrivals.

Figure 5 compares actual route and altitude flight plan amendments from the Host traffic recording to the route and altitude amendments generated in the laboratory simulation using the identical Host traffic recording to initialize the simulation. Note the substantial difference – about a factor of 8 – in the number of amendments, particularly temporary altitude amendments, issued in real operations vs. the number issued in the simulation where the system was configured to only resolve traffic conflicts. This result suggests that many Host amendments are being entered by controllers and possibly given as clearances to aircraft for reasons other than separation. Controllers are likely being conservative to ensure that uncertain climb profiles do not cause short-term conflicts with crossing or merging traffic.

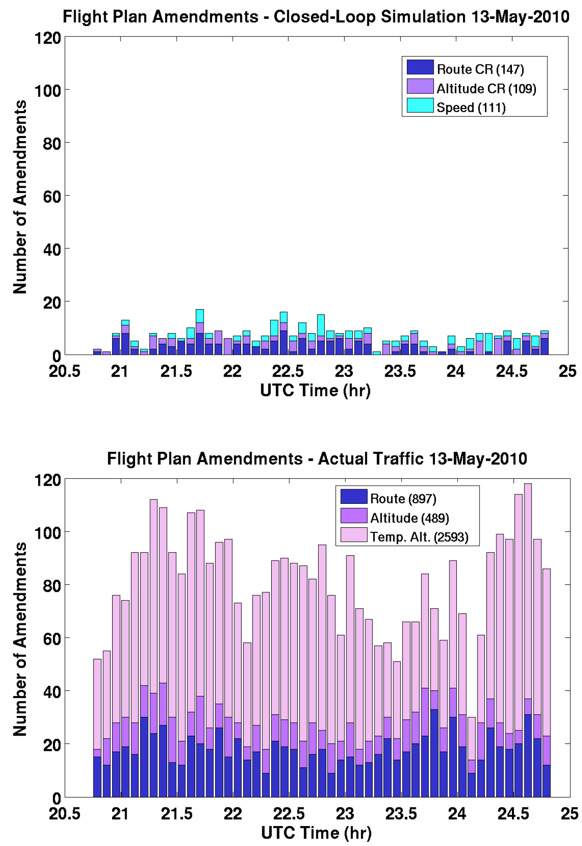


Figure 5. Comparison of actual Host and simulation flight plan amendments for common traffic sample.

4.2 Loss of Separation (LoS) Analysis

Following each simulation run the simulated radar track recordings were analyzed to identify LoS cases where aircraft passed closer than the legal separation criteria for en route airspace (5 nmi horizontal or 1,000 ft vertical). An analysis of LoS cases reveals problems with the trajectory automation, the concept, and the software. It was noted early in our analysis that most of the LoS cases were occurring at

altitudes below 15,000 ft. Many were less than 3 min after simulation initialization or involved arrivals below 15,000 ft merging to the meter fix. Controllers typically issue fine speed adjustment clearances to maintain 5 nmi spacing during the last few minutes before aircraft cross the meter fix at 10,000 ft. The trajectory automation does not compute such speed clearances. So, in order to scope the problem, a decision was made to analyze only those LoS cases that occurred at or above 17,000 ft.

Figure 6 summarizes the LoS results for the 32 traffic samples run under 3 different conditions:

- *No uncertainty* with strategic conflict detection and resolution (CD&R) (Test Condition 1)
- *Uncertainty* with strategic CD&R (Test Condition 1)
- *Uncertainty* with strategic CD&R and post-run tactical CD&R (Test Condition 4)

Figure 6 shows number of LoS cases, traffic level, and resolution count for each traffic sample. Traffic samples on the x-axis are ordered by increasing peak traffic count and indicated by traffic date (in 2010), UTC start time, and run duration in hours. The peak traffic count is scaled by a factor of 5 (to reduce clutter). The bars show LoS count for each of the 3 run conditions.

The most important result from Fig 6 is that when Strategic and Tactical CD&R are integrated and run under uncertainty conditions, the 7 LoS cases (red bars) are *all* due to automatic descent clearances (see Fig. 8) inherent to this laboratory analysis without human operators. These LoS cases would not occur in real-world operations under this TBO concept for two principal reason. First, a controller would not intentionally descend (or climb) a level-flight aircraft onto crossing traffic. Secondly, unlike today's Conflict Alert, the Tactical Automation function checks altitude amendments for conflict before the aircraft starts climbing or descending. The controller is alerted before the aircraft starts the maneuver and would be able to prevent the LoS. It is important to note that in order for this tactical safety net to work properly, the altitude amendment must be input to the Host (or ERAM) before the clearance is issued to the aircraft.

In all other LoS cases in this analysis, the replay with Tactical Automation prevented the LoS and did not create any other LoS cases with secondary traffic (aircraft not involved in the original detected conflict).

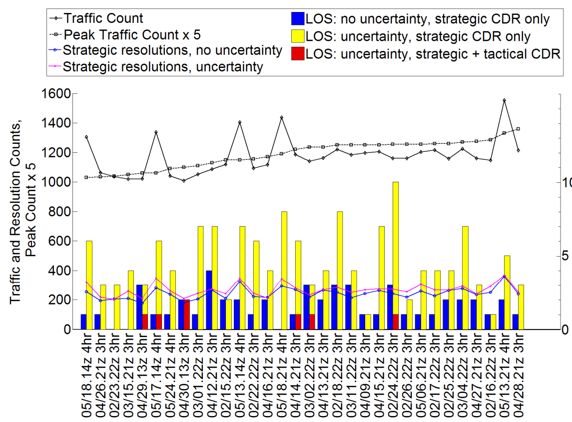


Figure 6. Loss of separation summary.

Figure 6 also shows that the number of resolutions under uncertainty is only roughly 10% higher than in the no-uncertainty conditions. This is consistent with the aggregate results in Fig 2. Also note that for today's traffic levels LoS statistics are generally not a function of traffic level or peak traffic level, and resolution count rises with traffic level but not peak traffic level as might be expected.

All of the LoS cases in the three simulation conditions (no-uncertainty with strategic CD&R, uncertainty with strategic CD&R, and uncertainty with strategic and tactical CD&R) were examined to determine their causes. The results are summarized in Figure 7. It should be noted that 91% of LoS cases are attributable to errors in climb and descent predictions. Clearly, top-of-descent (TOD) prediction errors lead to the largest number of LoS cases in this analysis. A 10% error in aircraft weight combined with a 10 kt wind error can cause a 4 nmi error in TOD prediction, and other factors (e.g., speed intent and model errors) can make the error even greater. Good TOD predictions (or ways to accommodate TOD uncertainty) are important

to achieving workable and reliable fuel-efficient descent profiles in medium to heavy traffic, and are needed to keep corrective clearances from generating excess controller workload. Typical examples of selected LoS cases are now examined in more detail here.

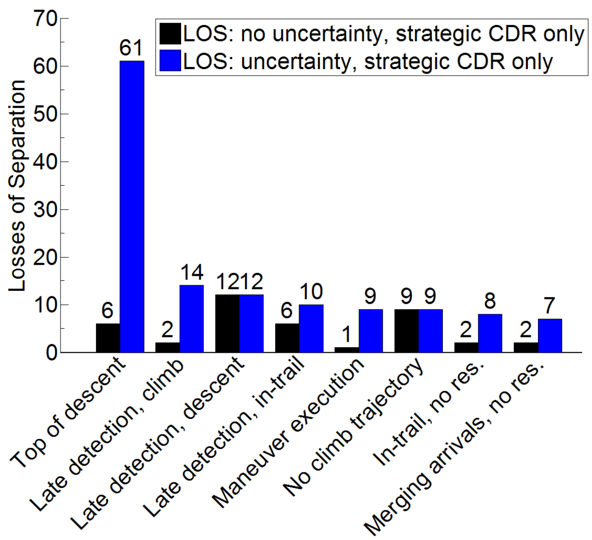


Figure 7. Causes of separation losses.

Shown in Figure 8 is a typical example of a LoS caused by TOD prediction error. Since there are no human operators in this simulation, the aircraft just descends into crossing traffic at its fuel-efficient TOD point. As discussed earlier, controllers would normally catch this and issue the descent clearance earlier or later. The TSAFE Tactical Automation would also alert the controller and prevent the LoS under the occasional cases where the controller does not see the crossing traffic. (In future simulations, TSAFE functionality will be added to the real-time system to prevent altitude clearances from causing an immediate LoS.)

The result (illustrated in Fig 8) that is more relevant to TBO is that errors in TOD predictions cause aircraft to deviate from their fuel-efficient descent profile because corrective actions are required to prevent LoS near TOD points. Likewise trajectories for non-descending aircraft flying near regions where other aircraft are beginning their descent could miss a conflict with the descending aircraft resulting in additional corrective clearances. In the Fig 8 example, had the TOD prediction been accurate the conflict resolution issued at 8 min to LoS would have been successful and not required a corrective action to avoid the LoS. It is believed that TOD prediction error and descent profile prediction error are the principal reasons for procedural separation of crossing traffic in regions where aircraft are near their TOD point.

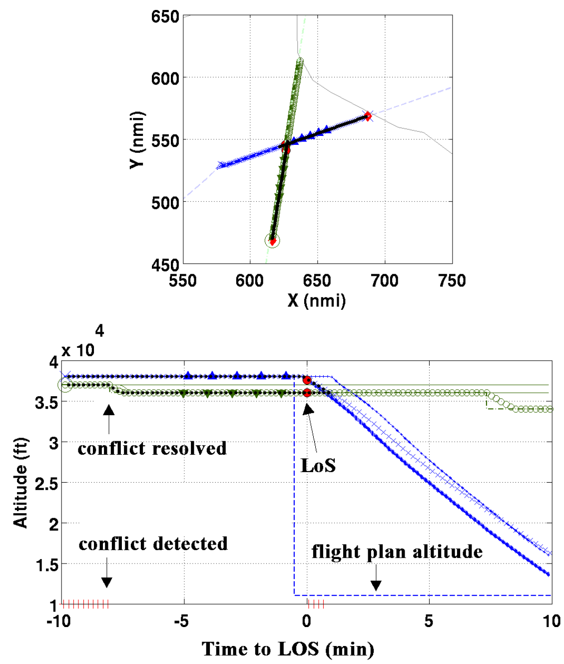


Figure 8. Top-of-descent prediction error

The Efficient Descent Advisor [21] partially solves the TOD prediction error problem by using descent speed clearances to ensure that the aircraft and the trajectory automation system use the same descent speed profile (which influences the fuel-efficient TOD point). However, recent operational test results show that TOD prediction errors can still be on the order of 5-10 nmi [21]. Methods to improve TOD predictions, perhaps through downlink [50] of the aircraft's preferred TOD point or other information, will be the subject of future research.

Shown in Figure 9a is a LoS caused by maneuver execution delay which involved two aircraft merging to the NE arrival fix (DEBBB) for Dallas/Fort Worth arrivals. The conflict was detected at 4.5 min to LoS. After several iterations the resolver issued a right turn path stretch amendment for the MD83, but with

approximately 1 min of maneuver execution delay in this case, a LoS occurred. This is a clear indication that excessive maneuver execution delay will not be acceptable in scenarios involving merging arrivals, and likely any cases that involve conflicts with acute closure angles and the desire (or need) for path stretch resolution maneuvers.

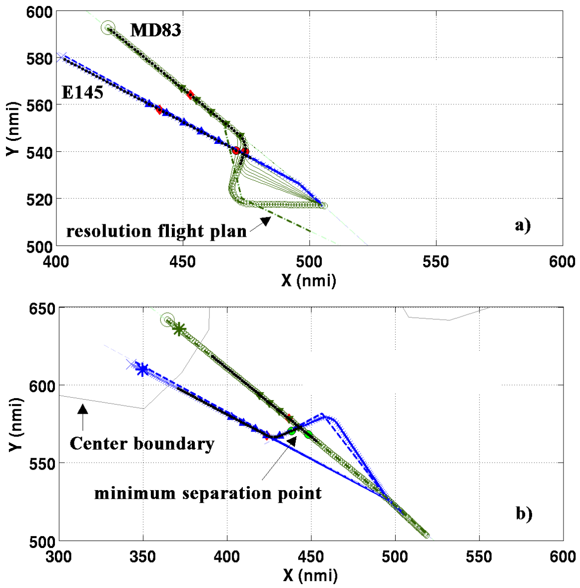


Figure 9. Maneuver execution delay example, a) LoS with delay, b) no LoS without delay.

The full traffic scenario was replayed with wind and weight uncertainty, but maneuver execution uncertainty set to zero. LoS cases for strategic-only CD&R dropped from 8 to 6. As shown in Fig 9b, the conflict was successfully resolved at 7 min prior to loss. Note that in the replayed scenario, the other aircraft (E145) was maneuvered, likely because it had the lower resolution delay.

It should be noted that the EDA function requires that arrival aircraft begin path stretch maneuvers at a known starting point that is computed by the automation and delivered as part of the clearance [21]. This effectively eliminates maneuver execution delay from path stretch clearances for merging arrivals. These results, combined with EDA results, strongly suggest that for minimum-fuel descent trajectories to be successful, it will be required that the concept reduce maneuver execution delay by including a more precisely-defined maneuver start point as part of the clearance.

Several of the LoS cases involving arrivals merging to a common fix were caused by the autoresolver's inability to determine a conflict-free solution during busy arrival flows and crossing traffic using the nominal resolution criteria (8 nmi) in Table 1. However, when the simulation was replayed using horizontal detection and resolution criteria slightly reduced from 6 & 8 nmi to 5 & 7 nmi, the resolver was able to successfully resolve the merging arrival conflict. One such case is illustrated in Figure 10. The conflict was resolved, while keeping the maneuvered aircraft on its fuel-efficient descent profile, with a minimum separation of 7.9 nmi and 4,400 ft. This result along with the previous maneuver execution delay example (Fig 9), and knowledge of today's arrival metering operations, confirms the need for tighter tolerances for successfully handling busy merging arrival flows.

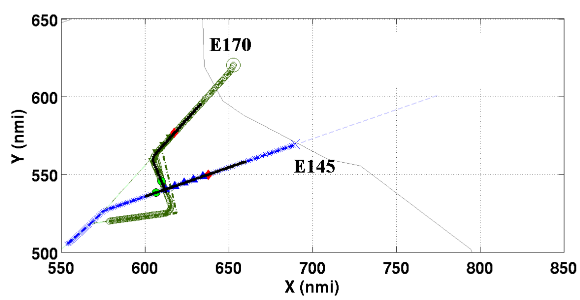


Figure 10. Merging arrival, successful when resolution criteria reduced from 8 nmi to 7 nmi.

4.3 Multi-Trajectory Conflict Detection for Climbing Flights

Thirteen losses of separation were identified to be caused by climb trajectory prediction uncertainty. Nine of these cases had first detection times of less than or equal to two min. An example involving two climbing flights is shown in Figure 11. These nine cases were played back with the multi-trajectory conflict detection algorithm enabled. In this analysis the algorithm was enhanced to more effectively handle conflicts between: 1) climbing and non-climbing (i.e., level or descending) flights, and 2) two climbing flights. It was necessary to decompose the algorithm into these two pieces because climb/non-climb conflicts involve one

set of fast- and slow-climb trajectory predictions, whereas climb/climb conflicts involve two sets. The details of the extended algorithm are presented in Appendix B.

The alert lead times at first detection for the nine cases using the multi-trajectory (dynamic) conflict detection algorithm were compared to their respective times using the nominal detection algorithm. Results indicated that seven of these nine cases would have been detected in time and most likely resolved if the dynamic algorithm had been running (see Figure 12). Additional offline investigation using Matlab to perform dynamic conflict detection found that these two conflicts should have been detected 8.6 and 5.0 minutes prior to first loss, respectively (a software bug prevented early detections in the CTAS system).

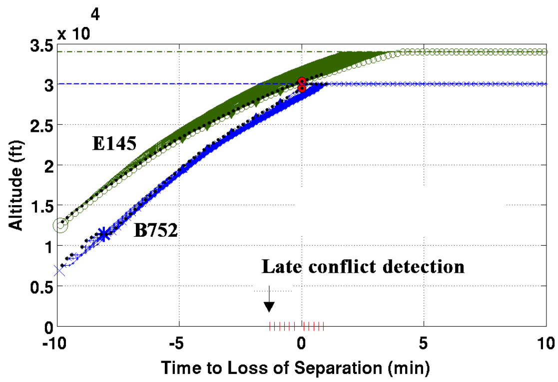


Figure 11. Late detection climb example, two aircraft climbing in-trail

The multi-trajectory conflict detection algorithm was also tested in a simulation run in which Minimum-Delay Conflict Resolution was enabled. The 4/12/2010 scenario starting at UTC 1400 was selected because it had the most (two) LoS cases due to climb uncertainty. One case involved a climbing flight and a level flight, and the other case involved two climbing flights (Fig 11). Overall, there were seven LoS cases in the nominal simulation run. By comparison, when dynamic separation was utilized, the total number of LoS cases dropped to two and, more importantly, there were no LoS cases due to climb uncertainty.

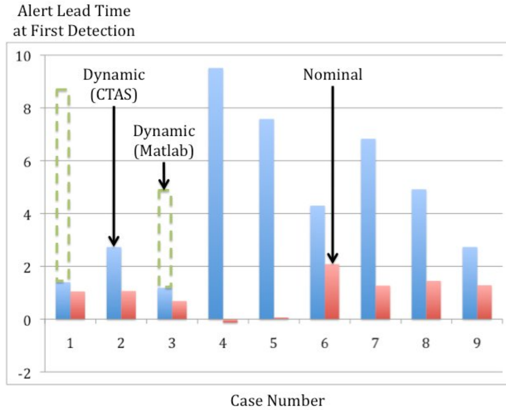


Fig 12. Alert lead time at first detection with and without dynamic conflict detection for climbing flights (9 LoS cases).

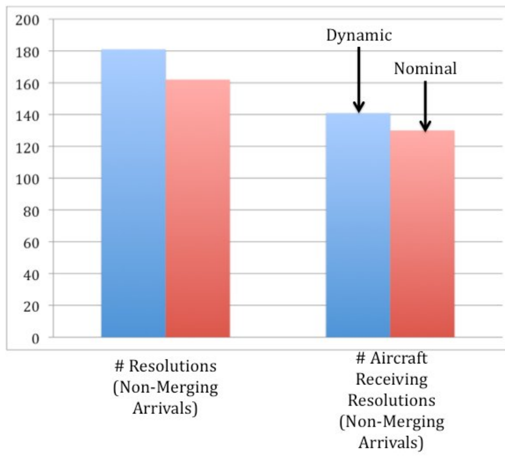


Figure 13. Conflict resolution analysis for dynamic and nominal detection for climbing flights.

Figure 13 compares the number of resolutions issued using the nominal and multi-trajectory (dynamic) conflict detection algorithms. The dynamic separation algorithm issued about 12% more resolution maneuvers than the nominal algorithm in non-merging arrival cases. The reason for this is because it uses larger conflict detection criteria. However, this difference is less than prior analysis using actual Host radar track data [34]. Besides differences between the simulation and actual traffic, it can also be attributed to refinements made to the dynamic separation algorithm since the earlier study. The number of resolutions issued in merging arrival cases was about the same since the dynamic algorithm is only utilized for climbing flights.

The multi-trajectory climb conflict detection algorithm was tested on recordings of flights departing the Dallas/Fort Worth TRACON. For the single 3-hour period examined, about 1/3 of the flights had temporary altitudes at some time during their climb from 10,000 ft to their cruise altitude. The conflict status of a direct-climb-to-cruise-altitude trajectory was computed during the time intervals where temporary altitudes were active in the traffic recording. It is interesting to note that in only 13 out of 42 flights (31%) were conflicts detected on the direct climb to cruise trajectory during the temporary altitude time interval. This suggests that a trajectory-based system with a more robust climb conflict detector could enable 69% of these climbers to fly uninterrupted to their cruise altitude without the need for temporary altitude clearances.

4.4 Wind-Favorable Direct Route Results

In order to investigate the effect of wind favorable direct routes on overall system performance the Direct-To (D2) algorithm in CTAS [28] was configured to automatically issue as flight plan amendments all conflict-free D2 routes for aircraft at or above flight level 240 (FL240). FL240 was chosen because it is the lower boundary of the high altitude airspace in Fort Worth Center and considered a conservative estimate of the altitude at which many direct routes start to become feasible in today's operations. The automatic D2 function and the Minimum-Delay Conflict Resolution function are run simultaneously on 10 traffic samples with large peak traffic levels. The delay histogram is shown in Figure 14, and the loss of separation results are summarized in Figure 15.

Note from Fig 14 that the delay characteristics for the conflict resolution trajectories (all but the auto D2 trajectories) are similar to those shown in Fig 2b where auto D2 was not enabled. The overall mean delay drops from 1.1 min (Fig 2b) to 0.2 min (Fig 14). And the total flying time savings for the D2 trajectories was 269 min over a 4-hour full-Center traffic sample where 107 out of 1553 aircraft in the simulation were issued D2 clearances. The average savings per D2 clearance is 2.5 min, which is consistent with the results in [28].

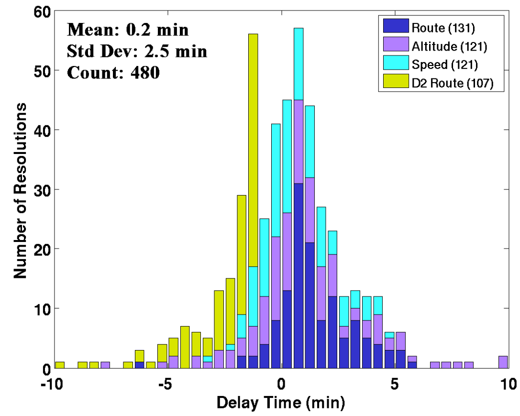


Figure 14. Delay histogram for sample auto Direct-To run (05/13/10.21z).

Note from Fig 15 that there were generally fewer LoS cases in the auto D2 runs, but more of them (6) were not resolved by the TSAFE Tactical Automation. Examination of the data revealed that all the LoS cases were due to the TOD error scenario described earlier in this section (Fig 8).

The important point here is that a total flying time savings of 269 min was realized with a minimal impact on overall conflict detection and resolution metrics. These results also illustrate the point that better TOD predictions would enable more fuel-efficient routings for other aircraft, such as these aircraft that received wind-favorable direct routes.

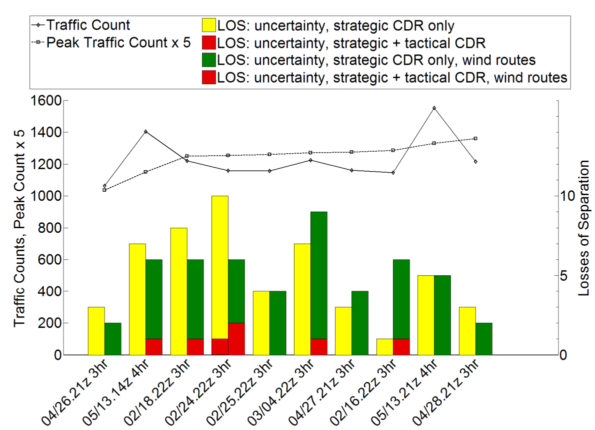


Figure 15. Loss of separation summary for auto Direct-To runs.

5 Conclusions

A near-term concept for trajectory-based operations in today's air traffic environment has been defined, and a prototype of its required real-time ground-based trajectory automation system has been developed and tested in the laboratory.

Results clearly demonstrate under a wide variety of traffic conditions that state-of-the-art real-time 4D trajectory automation can provide minimum-delay solutions to traffic conflicts, identify time/fuel-efficient flight trajectories, and substantially reduce the number of clearances compared to today's operations.

All trajectory-based clearances can be delivered using route, altitude, and speed changes commonly issued by controllers in today's air traffic operations, and all clearances are suitable for datalink delivery using currently available integrated FMS/datalink with CPDLC.

Results are based on analysis of 102 hours of busy traffic periods from 30 days in 2010 including over 37,000 actual flights from the FAA's Fort Worth Air Route Traffic Control Center, and the simulation analysis included uncertainty modeling for aircraft weight, pilot maneuver execution delay, and wind forecast errors.

When strategic and tactical automation are integrated as described in the concept, loss of separation is preventable. In all but one specific category of cases (immediate loss due to un-probed climb or descent clearances) trajectory automation prevented loss of separation in all airspace above 17,000 ft.

Minimum-delay strategic conflict resolution trajectories and their associated route, altitude, or speed clearances were automatically generated for 89% of conflicts for all traffic above 11,000 ft. It is expected that improvements to the resolution logic or suitable adjustments to run-time parameters will increase performance to near 100%.

Overall conflict detection and resolution statistics are not impacted by the automatic implementation of wind-favorable direct routes above Flight Level 240; flying time savings associated with these reroutes sums to 269 min over a 4-hour traffic period.

Excessive maneuver execution delay is not tolerable for arrivals merging to a common fix. In order to reliably achieve fuel-efficient descent profiles in busy merging arrival flows, it is required that the concept reduce maneuver execution delay by incorporating a more precisely defined start point as part of the trajectory-based clearance.

Top-of-descent prediction errors are the leading cause of failure in this analysis. Good top-of-descent predictions are needed to reliably achieve fuel-efficient descent profiles in medium to heavy traffic, and to minimize corrective clearances for arrivals and other traffic. Future research should address methods to either reduce top-of-descent prediction errors or adjust the concept to accommodate them.

Multi-trajectory conflict detection for climbing flights eliminates all losses of separation due to climb prediction uncertainty, the 2nd leading cause of separation loss without the tactical safety backup. It could also be the basis for substantially fewer temporary altitude clearances during climb segments.

Unlike today's Conflict Alert, tactical automation must alert when an altitude amendment is entered, but before the aircraft starts to maneuver. In all other failure cases in this analysis the tactical automation function prevented loss of separation.

Appendix A Trajectory prediction error histograms: prediction v. Host tracks and prediction v. simulated tracks.

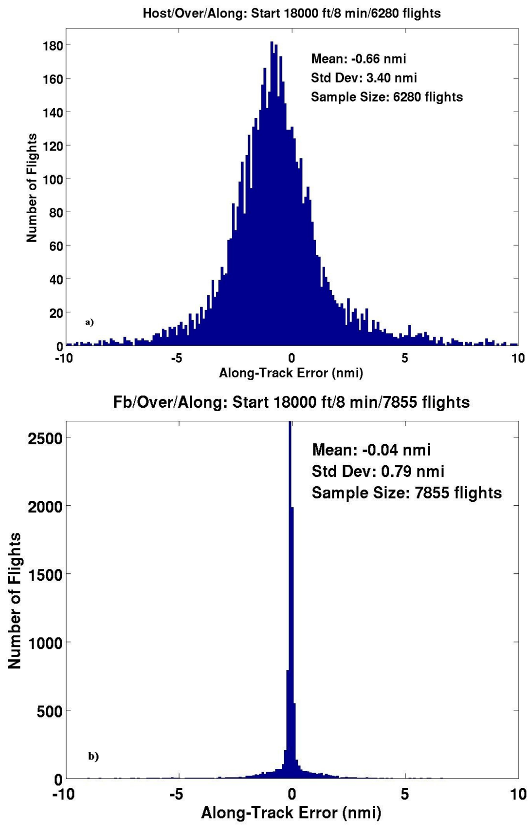


Fig A1. Level flight along track error, a) prediction v. actual Host tracks, and b) prediction v. simulated tracks.

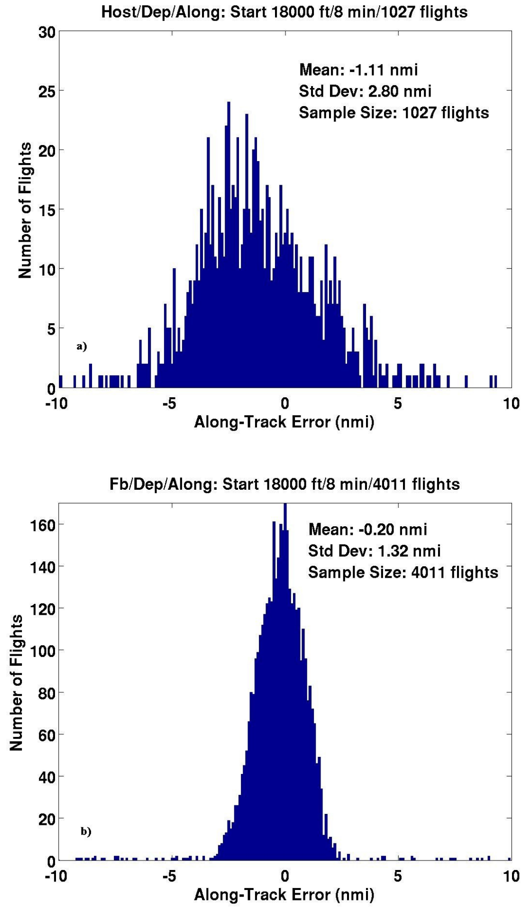


Fig A2. Climbing along track error, a) prediction v. actual Host tracks, and b) prediction v. simulated tracks.

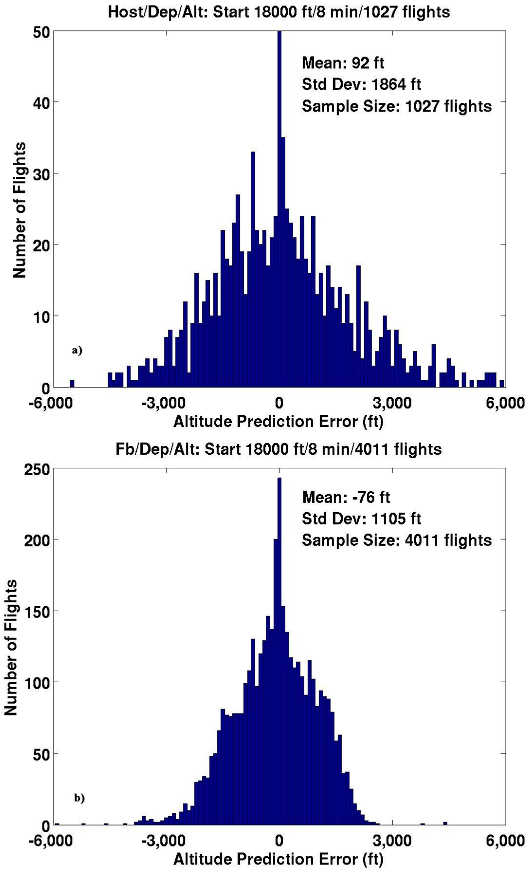


Fig A2. Climbing vertical error, a) prediction v. actual Host tracks, and b) prediction v. simulated tracks.

Appendix B

The dynamic conflict detection algorithm checks the volume of airspace between the fast- and slow-climb trajectories of climbing flights for conflicts by using these trajectories to define dynamic vertical and horizontal detection criteria around the nominal trajectory of the climbing flight at each trajectory time step. Dynamic horizontal detection criterion at each time step is the nominal conflict detection criterion of 6 nmi plus the maximum of: 1) the horizontal distance between the fast- and nominal-climb trajectories, and 2) the horizontal distance between the nominal- and slow-climb trajectories. Vertically, the climb envelope is composed of dynamic "upper-vertical" and "lower-vertical" detection criteria that are functions of look-ahead time:

$$u_i(t) = h_{i,f}(t) - h_{i,n}(t) + V \quad (1)$$

$$l_i(t) = h_{i,n}(t) - h_{i,s}(t) + V \quad (2)$$

where $h_{i,j}(t)$ = predicted altitude of climbing aircraft i at time t for j-climb trajectory, $j \in \{f, n, s\}$ (f: fast, n: nominal, s: slow), and V = minimum vertical separation criterion

The equations for computing upper- and lower-dynamic vertical detection criteria for climb/climb conflicts have been revised to reduce false alerts. Note that they are more complex than in the climb/non-climb case since they involve two sets of fast- and slow-climb trajectory predictions instead of just one. Equations 3 and 4 are for the cases where AC1 is below AC2 and vice versa, respectively:

$$u_1(t) = \begin{cases} h_{2,n}(t) - h_{1,n}(t) + V, & \text{if } h_{2,s}(t) - h_{1,f}(t) < V \\ h_{1,f}(t) - h_{1,n}(t) + V, & \text{otherwise} \end{cases} \quad (3)$$

$$l_1(t) = \begin{cases} h_{1,n}(t) - h_{2,n}(t) + V, & \text{if } h_{1,s}(t) - h_{2,f}(t) < V \\ h_{1,n}(t) - h_{1,s}(t) + V, & \text{otherwise} \end{cases} \quad (4)$$

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